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OBSERVATIONS ON ELECTROSTATIC EFFECTS IN A FILTER TEST SYSTEM (U)

by

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ABSTRACT

The filter test system FTS 400 was used to examine a variety of filter papers, using NaCl and DOP as aerosol challenges. In nearly every case a minimum in penetration was observed at particle size in the vicinity of 0.02 µm. In the same region NaCl particles (but not DOP droplets) exhibited substantial in-line losses which could affect measured penetration results. Introduction of a radioactive neutralizer which removes most of the particle charge greatly reduced line losses.

The effect of introducing the neutralizer on penetration was studied, using several types of filter paper. Conventional filter papers showed a slight increase in penetration over the size range up to 0.3 µm. With electrets, which depend on electrical attraction for their effectiveness, introduction of a neutralizer increased penetration in the same range by several orders of magnitude.

RÉSUMÉ

Le système d'essai des filtres FTS 400 a été utilisé pour examiner une variété de papiers-filtres dans des épreuves avec des aérosols de NaCl et de DOP. Dans presque tous les cas, on a observé une pénétration minimale avec des diamètres de gouttelettes d'environ 0,02 µm. Dans cette même plage de diamètres, les gouttelettes de NaCl (et non celles de DOP) restaient accrochées dans une proportion appréciable aux parois des canalisations, ce qui a pu fausser les mesures de pénétration. L'introduction d'un neutralisant radioactif qui élimine la plus grande partie de la charge des gouttelettes a réduit considérablement les pertes.

L'effet du neutralisant sur la pénétration a été étudié au moyen de plusieurs types de papier-filtre. Les papiers-filtres ordinaires ont ainsi vu leur pénétration augmenter dans la gamme des diamètres allant jusqu'à 0,3 µm. Quant aux électrets, dont l'efficacité dépend de l'attraction électrique, le neutralisant a eu pour effet d'augmenter leur pénétration, dans la même gamme, de plusieurs ordres de grandeur.

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1.0 INTRODUCTION

The filter test system FTS 400[1] makes possible the measurement of filter penetration as a function of particle or droplet size. To generate a challenge in the size range[2] 0.01 to 0.31 μm, it employs a TSI instrument, the electrostatic classifier, which selects a narrowly homogeneous (monodisperse) aerosol from an initially heterogeneous aerosol of dioctyl phthalate (DOP) or NaCl. Discrete sizes greater than 0.3 μm are obtained using monodisperse aqueous dispersions of polystyrene latex spheres (PSL) in another generating apparatus. Details of this system have been given elsewhere (1).

Using this system we observed for a variety of filter media a maximum in penetration generally in the neighbourhood of 0.2-0.3 μm, in agreement with earlier observations and theoretical predictions, and a fall in penetration on each side of this range. It was found however that the percent penetration after falling at sizes below 0.2 μm then rose on approaching 0.01 μm, the lower end of the classifier's output, so that an apparent minimum in penetration resulted, most commonly around 0.02-0.05 μm.

This minimum is not predicted by current theories of filter action, and so far as can be ascertained has not been observed previously. The present work was undertaken in the first place to examine the phenomenon, in particular to determine if it is real or an instrumental artefact. A number of experiments supported the idea that the effect was in part associated with the charges on the particles. To examine this idea, the aerosol charge distribution was modified by introducing into the aerosol stream a "neutralizer" to be described below. The effect of the neutralizer on both standard (uncharged) and electretted filter media was investigated, and this work suggested in turn a way to separate the electrostatic and mechanical contributions to filtration.

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[1] Designed and constructed by TSI Inc., St. Paul, Minnesota, USA.

[2] Particle and droplet sizes are diameters, in accordance with usual practice.

2.0 ROLE OF CHARGE IN FILTRATION

2.1 AEROSOL CHARGE

Aerosols produced by the usual means - mechanical dispersion, evaporation - condensation, etc have non-equilibrium frictional charges often of considerable size. Current investigations of filter behaviour are generally not concerned with the complications created by charged particles, although charge effects in the interaction of single fibres and particles have been considered (2). In some recent investigations this interference has been reduced by passing the aerosol through a neutralizer. The most convenient form of this is a radioactive source, a β-emitter which establishes in the aerosol stream an excess of positive and negative ions; these ions diffuse to the aerosol particles and reduce their charge to a level corresponding to the Boltzmann equilibrium.

Charged particles are trapped in a filter more efficiently than uncharged, either by direct attraction to static charges already present on the filter fibres, or more generally by the operation of image forces arising from charges induced by the approaching particle. Instances of this enhanced efficiency are cited by Whitby and Liu (3). Additionally, the presence of a charge on aerosol particles may increase losses by deposition on the walls of the transport line before the filter is reached, i.e. reduce the measured upstream concentration.

It follows from the principle of operation of the classifier that every particle or droplet of aerosol produced has a single positive charge (apart from a minor proportion of doubly charged particles). This, for aerosols in the few hundredths of a micron range is an artificial situation, as is seen on comparing it with the Boltzmann equilibrium distribution, which the aerosol will ultimately reach in the presence of an atmosphere of positive and negative ions. The equilibrium distribution has been calculated for a suspension of aerosol particles, as a function of particle size, by Pui and Liu (4) whose results are reproduced in Table I below.

TABLE I

Percent of particles carrying n elementary charge units

D, μm	n=-4	-3	-2	-1	0	+1	+2	+3	+4
0.01				0.34	99.32	0.34			
0.02				5.23	89.53	5.23			
0.04			0.23	16.22	67.10	16.22	0.23		
0.06		0.01	1.25	21.30	54.88	21.30	1.25	0.01	
0.08		0.08	2.78	23.37	47.53	23.37	2.78	0.08	
0.10		0.26	4.39	24.09	42.52	24.09	4.39	0.26	
0.20	0.32	2.33	9.66	22.63	30.06	22.63	9.66	2.33	0.32
0.40	2.19	5.92	12.05	18.44	21.26	18.44	12.05	5.92	2.19
0.60	3.82	7.41	11.89	15.79	17.36	15.79	11.89	7.41	3.82
0.80	4.83	7.94	11.32	14.00	15.03	14.00	11.32	7.94	4.83
1.00	5.42	8.06	10.71	12.70	13.45	12.70	10.71	8.06	5.42

At equilibrium, nearly all 0.01 μm particles are uncharged; with larger sizes a symmetrical distribution of positive and negative charges is established, the uncharged component being always the largest one.

2.2 CHARGED FILTER MEDIA

Filters made of electretted materials have received considerable attention in recent years. They rely for their effectiveness on the attraction exerted by permanent charges on the filter fibres rather than on mechanical modes of particle capture; and they combine good efficiency with a very low resistance to air flow. The theory of their operation has been discussed, most recently by Pich et al (9). Several products of the 3M company were examined in the course of this work.

3.0 EXPERIMENTAL

Operation of the FTS 400 is detailed in the manufacturer's manual, and was followed with a few modifications mentioned in Reference 1. In the original system the monodisperse aerosol from the classifier is conducted by a $^1/_2$" diameter x 34" steel tube to an air dilution manifold and thence by a large tygon inlet tube to the test chamber. For experiments in which the neutralizer was to be used, this was replaced by a 100 ml glass pipette fitted at both ends (after removal of the constricting delivery tip) with tygon tubing and appropriate couplings. The source was applied to the barrel of the pipette. The neutralizer was a 100 millicurie Sr^{90} source contained in a flat cylinder. The isotope was recessed in one face of the cylinder and emitted β particles unidirectionally. The source was used with lead shielding to reduce bremstrahlung to a safe level. Rough calculations, comparing half-life and β particle energy with those of the 2 millicurie Kr^{85} neutralizer commercially available (TSI 3071) make it clear that more than enough radiation passes through the glass pipette walls to reduce the aerosol in transit to the equilibrium charge state.

Classifier output is quite constant, within a few percent, except at the smallest sizes. Thus, concentration of 0.01 μm NaCl can vary unpredictably from 10^2 to 2-3 x $10^3/cm^3$ (though fluctuations are usually smaller on any given day); while at 0.2 μm the variation is commonly 3-4% in successive runs, and the extreme values observed over a period of weeks differ by a factor of less than two. In the work that follows the results of consecutive experiments carried out over a short time are compared.

All experiments are conducted at a flow rate of 16 LPM, corresponding to a linear flow velocity of 13 cm/sec at the filter face.

4.0 RESULTS AND DISCUSSION

4.1 MINIMUM AEROSOL PENETRATION IN THE RANGE 0.01-0.30 μm

This phenomenon was quite general, being observed with both NaCl and DOP. In all some 70 tests were conducted, with filter media of every degree of efficiency from quite good to poor. Only a few materials of very poor performance overall did not exhibit this minimum.

Table II shows a selection of results obtained with a variety of filter materials. Minimum penetration values are underlined. All experiments except one (in Table II(c)) were conducted with the FTS as originally supplied (no neutralizer in place).

TABLE II

Percent Penetration of Various Media as a Function of Particle Size

Challenge: (a) NaCl Aerosol								
Diameter (μm)	.01	.02	.03	.05	.10	.15	.20	.30
DREO 3310[1]	.00128	.00083	-	.0109	.088	.092	.091	.025
DREO 3313	3.39	2.11	-	11.4	23.2	23.3	31.1	21.3
DREO 3320	.403	.095	-	1.54	5.48	4.88	4.98	2.54
PALL 10182G[2]	.0112	.00026	.00015	.00117	.0122	-	.0228	.0048
3M GO 110[3]	4.03	.0240	.0113	.00745	.051	.626	2.08	4.7
3M GO 120	.788	.00727	.00380	.00233	.00394	.0220	.116	.235
3M GO 130	.217	.0040	.0015	.00097	.00043	.00103	.00512	.0166
KLEENGUARD[4]	19.0	7.4	17.8	23.8	50.4	-	56.5	52.3

[1] The DREO 3300 series are experimental handsheets developed for the respirator particulate filter.

[2] A product of Pall Canada Ltd.

[3] A fibrous loose fabric, with permanent electric charges on the fibres. A product of the 3M Company. 110, 120, 130 indicate increasing thickness in the ratio 1:2:3.

[4] A product of Kimberly-Clark. A coverall material based on polypropylene.

TABLE II (cont'd)

Challenge: (b) DOP Aerosol								
Diameter (μm)	.01	.02	.03	.05	.10	.15	.20	.30
DREO 3310	.0154	.00026	-	.0068	.0171	.0304	.0460	.0446
DREO 3314	40.9	20.8	-	48.6	25.5	54.7	72.4	58.9
DREO 3313	14.2	1.05	-	10.6	10.1	23.6	23.5	16.3
PALL 10182G	.0242	.0180	.000655	.00652	.0557	-	.0889	.0271
3M GO 110	41.8	.3750	-	.0222	.391	1.99	4.60	10.43
3M GO 120	6.42	.138	.0196	.0076	.0042	.00794	.0308	.165
3M GO 130	9.0	2.12	.104	.037	.0155	.053	.154	.62
(c) NaCl - Filters with no minimum penetration								
Diameter (μm)	.01	.02	.03	.05	.10	.15	.20	.30
DREO 3314	19.9	29.0	-	41.7	77.1	57.6	72.1	69.9
DREO 3321	1.16	1.82	-	11.6	22.7	23.2	24.8	20.0
KLEENGUARD WITH NEUTRALIZER IN AEROSOL DELIVERY LINE	7.8	15.3	19.8	27.1	47.1	-	54.6	49.3

4.2 EXAMINATION OF INSTRUMENTAL PHENOMENA

A variety of experiments are described below, intended to determine the effect of altering the aerosol charge state on losses of NaCl and DOP, both upstream of the test chamber and in the sampling lines. Losses that may occur upstream of the filter are of no great concern, but any differential losses when sampling by upstream and downstream sampling lines could call directly in question the validity of filter efficiency results. It is of course assumed in the test system design that these losses are small and self-compensating.

4.2.1 Effect of Change in Connector

In preliminary work, the effect on aerosol concentration of simply replacing the original steel connecting tube by glass and tygon was investigated, using no neutralizer. Aerosol can be lost by attraction of particles to regions of static charge in plastic vessels and connectors, teflon being notorious in this respect. Measured upstream concentrations of NaCl and DOP, with the original and modified connection, are reported in Table III. No significant change resulted from the substitution.

TABLE III

Upstream Aerosol Concentrations (Particles/cm^3) with Two Delivery System.

Aerosol	Diameter (μm)	Original (Steel) Connector	Glass Pipette Tygon Tubing
DOP	0.01	1.9×10^2	2.3×10^2
	0.02	2.5×10^2	3.7×10^2
	0.05	8.0×10^4	8.3×10^4
	0.10	1.1×10^5	1.15×10^5
NaCl	0.01	4.4×10^2	1.8×10^2
	0.02	3.3×10^4	3.6×10^4
	0.05	2.3×10^5	2.4×10^5
	0.10	3.8×10^5	3.8×10^5
	0.20	8.3×10^4	8.3×10^4
	0.30	3.0×10^4	2.8×10^4

4.2.2 Charge Removal from Upstream Surfaces

The effect of pre-treatment of all upstream non-metallic connections with the neutralizer to remove static charge before generation of aerosol began was investigated. As the results of Table IV show, there is a perceptible increase in upstream concentration of the smallest size of NaCl, but otherwise no effect.

TABLE IV

Effect of Charge Removal from Upstream Surfaces
(Treatment with Neutralizer) on Delivered
Aerosol Concentration (Particles/cm^3)

	NaCl 0.01 μm	NaCl 0.03 μm	NaCl 0.3 μm	DOP 0.01 μm
Original	3.7×10^2	9.3×10^4	3.3×10^4	1.7×10^2
1st Treatment	4.0×10^2	9.6×10^4	3.3×10^4	1.2×10^2
2nd Treatment	4.2×10^2	9.5×10^4	3.3×10^4	1.6×10^2
3rd Treatment	6.9×10^2			

4.2.3 Differential Upstream/Downstream Sampling Losses

The upstream sampling path is a plastic tube $^1/_2$" i.d. by 18" long, from the upper part of the test chamber to a $^3/_8$"i.d. metal connection leading to a small chamber from which the measuring instruments draw. The downstream sampling path is all metal, the 4" diameter sample holder necking down to $^1/_2$" i.d. tubing from which a side tube $^1/_4$" i.d. by 6" long conducts aerosol to the same chamber.

If losses are about the same by both paths, then on running the instrument with no sample in place upstream and downstream concentrations should be approximately the same and a penetration of roughly 100% should be observed. Results for a number of experiments are collected in Table V.

TABLE V

Ratio (Downstream/Upstream Concentration) × 100
with No Sample in Test Chamber

(a) No Neutralizer							
Size	.01	.02	.03	.05	.10	.20	.30
NaCl	185	130	143	110	105	100	99
	418	134	145	110	102	99	99
	211	125	133	109	125	104	97
	197	124	132	110	102	101	98
DOP	93	90	136	116	103	100	99
	102	95	126	114	104	101	98

TABLE V (cont'd)

(b) With Neutralizer							
NaCl	98 96	104 99	106 104	104 101	98 101	101 101	108 98
DOP	90	90	100	105	101	100	99
(c) No Neutralizer - Upstream Sample Tube Rendered Conductive							
NaCl	209 172	127 119	132 122	112 112	102 102	102 101	100 99

At the smallest size of NaCl (but not DOP) large and variable losses must be occurring along the upstream sampling path. When the experiment was repeated with the neutralizer applied to the pipette, this differential loss was eliminated (Table V(b)).

This large upstream loss will have the effect of increasing the apparent penetration of singly charged 0.01 μm NaCl particles, and is referred to later in the discussion of filter penetration results. However it does not by itself explain the minimum in penetration at small size, which as will be seen later is observed also with aerosol treated with the neutralizer and substantially uncharged (cf. Table I) in this size range.

It seemed intuitively improbable that such losses could be due to static charge on the upstream sampling tube. To settle this point, the tube was removed, coated on the inside with conductive silver paint, and replaced. Repeating the experiment, again with NaCl aerosols and no neutralizer gave the results of Table V(c). The large losses persisted.

4.2.4 Neutralization of Upstream Sample

In another demonstration of the results of charge removal, the neutralizer was alternately applied to and removed from the plastic upstream sampling tube during a run, before the measuring instrument, the condensation nucleus counter, had registered a final upstream value. The running, continuously updated readings on the CNC display were observed.[1] With 0.01 μm NaCl, readings rose within 2-3 seconds from $4 \times 10^2/cm^3$ to $1.8 \times 10^3/cm^3$ on application of the neutralizer and fell as rapidly on its withdrawal. This could be repeated as often as desired. The effect was a function of aerosol size and material (Table VI). The effect falls off rapidly as NaCl size increases, and was absent with DOP.

[1] For a brief description of the CNC and other components of the FTS 400, see Reference 1.

These results are necessarily only approximate. Concentrations could not be allowed to reach their final steady values (as the program would have switched to downstream sampling) and the figures quoted are an average of the fluctuating CNC readout noted visually over a short period of time.

TABLE VI

Transient Upstream Measured Concentrations of Aerosol in Response to Irradiation of Sampling Tube (particles/cm^3)

Diameter (μm)		Unirradiated	Irradiated
NaCl	0.01	4×10^2	1.8×10^3
		1.3×10^2	7.5×10^2
	0.02	2.3×10^4	4.2×10^4
	0.03	9.5×10^4	1.35×10^5
	0.05	2.0×10^5	2.3×10^5
	0.1	3.65×10^5	3.8×10^5
	0.3	3.2×10^4	3.2×10^4
DOP	0.01	1.7×10^2	1.5×10^2

The absolute concentration of NaCl particles at 0.01 μm ($\sim 10^2$/cm^3) was much less than those at larger sizes ($10^4 - 10^5$/cm^3). There is the possibility that these surges in upstream concentration are spurious, due perhaps to dislodgement by β-radiation of particles from the tubing wall, noticeable against the 0.01 μm NaCl background but negligible elsewhere. Accordingly the classifier was set to select 0.3 μm NaCl, but with a low (0.01% w/w) NaCl solution as aerosol source. The resulting concentration of 0.3 μm NaCl aerosol (4.4×10^2/cm^3) was entirely unaffected by presence or absence of the neutralizer. Thus, the effect observed with 0.01 μm NaCl was due to this aerosol being transmitted with smaller losses following neutralization.

4.3 EFFECT OF NEUTRALIZER ON PENETRATION THROUGH STANDARD FILTER PAPER

In previous work (1) four filter paper specimens (HV4A)[1] were tested with NaCl challenge in the presence and absence of the neutralizer. The results reported there are presented again graphically in Figure 1 (average of four trials with standard deviation), and in Table VII.

Several facts are apparent. First, over most of the size range the aerosol treated with neutralizer, and containing a significant though variable proportion of uncharged particles, had an appreciably higher penetration than the singly charged output of the classifier.

TABLE VII

HV4A Paper Penetration (%) by NaCl

Diameter (μm)	Without Neutralizer	With Neutralizer
0.01	.0036 ± .0006	.0020 ± .0008
0.02	.000050 ± .000035	.00025 ± .00009
0.03	.000137 ± .000015	.0011 ± .0003
0.05	.0020 ± .0004	.0067 ± .0011
0.10	.021 ± .005	.028 ± .004
0.15	.024 ± .002	.032 ± .002
0.20	.023 ± .002	.031 ± .004
0.30	.0082 ± .0050	.0077 ± .0004

[1] A high efficiency filter paper produced by Hollingsworth and Vose, (East Walpole, Mass., U.S.A.) and designated HV4A by DREO.

However at 0.05 μm and below the scatter in experimental values was considerable, and the curves cross so that at the smallest size (0.01 μm) penetration was apparently greater for charged particles than for uncharged. A minimum at 0.02 μm was seen in both experiments.

In confirmation of the work with HV4A, tests were conducted with a second "conventional" aerosol filter paper, Pall 10182G. The results are presented in Figure 2 and Table VIII. Qualitatively the results support those obtained with HV4A. Somewhat greater sample-to-sample variation was noted, presumably a question of product uniformity.

TABLE VIII

Pall 10182G Percent Penetration by NaCl

Size (μm)	NaCl	
	Without Neutralizer	With Neutralizer
0.01	.0112 ± .0053	.00279 ± .00089
0.02	.000262 ± .000174	.000351 ± .000194
0.03	.000150 ± .000080	.00131 ± .00067
0.05	.00117 ± .00060	.00630 ± .00118
0.10	.0123 ± .0033	.0239 ± .0051
0.20	.0228 ± .0068	.0284 ± .0068
0.30	.0048 ± .0008	.0076 ± .0019

With NaCl, penetration by the neutralized aerosol was again greater.

A further examination of the difference between results obtained with these papers, with and without the neutralizer in line, is deferred until corresponding work with electrets has been described.

4.4 EFFECT OF CHARGE REMOVAL FROM ELECTRET FILTERS

It has long been known that electret materials can be discharged by exposure to X-radiation (5). We have observed that intense radiation (15 minutes exposure to unfiltered radiation from a Mueller MG 300, 300 kvp, 10 mA current, approximately 10 cm from window) leads to complete removal of charge, with slow recovery after several days of a small fraction of the charge. This affords a convenient means of demonstrating the dependence of electret filters on charge. Performance was compared before and after exposure of the filter to x-radiation, which neutralizes the charge while leaving the material physically unaffected. Figures 3 and 4 show the degradation in performance of 3M GO 110 and 130 filters inactivated by x-radiation and then challenged with NaCl and PSL. Figure 5 depicts corresponding results with DOP. The challenge material in these experiments was the singly charged output of the unmodified FTS.

4.5 EFFECT OF AEROSOL NEUTRALIZER ON PENETRATION THROUGH ELECTRET MEDIA

Varying the charge on the aerosol profoundly altered electret filter efficiency, far more so than with the uncharged filters.

Figures 6 to 11 show the performance of the three electret filters GO 110, 120 and 130 against NaCl and DOP aerosols in the absence and presence of a neutralizer in the line. Results with the unmodified filter test system have already been presented (Table II); those obtained with the neutralizer appear in Table IX.

TABLE IX

Penetration (%) of 3M Electret Filters by NaCl and DOP Aerosols Reduced to Boltzmann Charge Equilibrium

3M GO 110											
Diameter (μm)	.01	.015	.02	.03	.04	.05	.06	.10	.15	.20	.30
NaCl	24.0	33.7	39.1	31.8	27.0	-	23.5	9.6	9.4	8.5	6.3
DOP	42.4	-	29.0	42.2	-	38.6	-	24.2	14.0	11.8	10.8

TABLE IX (cont'd)

Penetration (%) of 3M Electret Filters by NaCl and DOP Aerosols Reduced to Boltzmann Charge Equilibrium

3M GO 120											
Diameter (μm)	.01	.02	.03	.04	.05	.06	.08	.10	.15	.20	.30
NaCl	1.72	7.12	9.0	8.76	-	7.20	6.45	3.86	1.75	1.44	.57
DOP	8.91	8.07	12.1	-	14.0	-	-	8.23	4.51	2.87	1.61
3M GO 130											
Diameter (μm)	.01	.015	.02	.03	.05	.07	.10	.12	.15	.20	.30
NaCl	.596	1.26	-	2.87	2.23	1.66	.68	.404	.204	.124	.034
DOP	2.94	-	3.03	4.38	5.46	-	1.91	-	.67	.29	.21

As discussed above, some uncertainty attaches to results at a size near 0.01 μm; but the penetration curves do clearly approach each other at the lower end. Similarly, at the upper end of the classifier range, near 0.3 μm, the curves again approach, indicating that at these larger sizes charged and neutral particles are retained with equal efficiencies. In preliminary experiments with these electrets and 0.916 μm polystyrene latex, with and without the neutralizer, nearly the same penetration was observed indicating again no charge effects with larger particles. In these experiments with PSL, the neutralizer was applied to the only accessible upstream point: the large plastic inlet tube conducting aerosol to the test chamber.

If one compares Figures 3 and 4, in which the filter is neutralized, with Figures 6 to 11, in which a sizeable neutral component is introduced into the impinging aerosol, it is seen that in the first case penetration increases over the entire size range covered (up to 2 μm). When, however, the aerosol is neutralized, increased penetration is noted only up to ~0.2-0.3 μm.

The percent penetration of GO 110 by 0.10 μm NaCl aerosol is 0.051% and 9.59%, without and with the neutralizer. In the first case the aerosol is uniformly in the +1 charge state; in the second, assuming the Boltzmann equilibrium to have been reached, the charge distribution is, 42.5% neutral, 48% ± 1 charge, and 9% ± 2 charge, and traces of more highly charged particles. Thus, 57.5% of the aerosol possesses some charge. As the electret depends so greatly on coulombic forces for its effectiveness, it is evident that the uncharged component must be responsible for the two orders of magnitude difference in penetration. Assuming in the simplest

case that all charged particles have the same penetration, equal to that of the +1 charged particles (0.051%) one can calculate the contribution to penetration ascribable to the charged component (57.5% of the total), as (.575 x .051%). Subtracting this rather small contribution from the total (9.59%), the penetration attributable to the uncharged component is 9.59 - 0.03 = 9.56%. Since this component represents only 42.5% of the total, what may be called its intrinsic penetration becomes

$$\frac{9.56}{.425} \text{ or } 22.5\%.$$

Where, as here, there is a great disparity in the two penetration values, the assumption of equal penetration for all charged species is not critical; if all penetrations are even of the same order of magnitude the final result is much the same. If one assumes, for example, that all charged particles are captured with 100% efficiency the calculation above reduces to

$$\frac{9.49}{.425} \text{ or } 22.6\%$$

the same as before. It is reasonable to suppose that +1 and -1 charged particles will be captured with about equal efficiencies on fibres that have areas of positive and negative charge and are electrically neutral overall. Multiply-charged particles which should be trapped more efficiently are only a small proportion of the total.

The assumptions become more questionable near the two ends of the size range, where the curves approach each other. At the upper end the penetration of charged particles becomes significant, and calculations at 0.01 μm are uncertain for reasons already discussed. With these reservations, calculated percent penetrations for neutral particles in the size range 0.02-0.03 μm are presented in Table X, for the three electrets and the two challenges. To facilitate comparison, the percent penetrations of the +1 charged particles are repeated. As would be expected, penetration decreases at greater filter thickness, passing from GO 110 to GO 130. In agreement with general experience, penetration of DOP is greater than that for NaCl in the same circumstances.

TABLE X

Penetration (%) of 3M Electret Filters by Singly Charged Particles (Experimental) and Neutral Particles (Calculated)

3M GO 110									
Size	0.02	0.03	0.04	0.05	0.06	0.10	0.15	0.20	0.30
Charged NaCl	.0240	.0113	.00627	-	.00862	.0505	.626	2.08	4.70
Neutral NaCl	43.5	42.1	47.5	41.6*	43.1	22.5	25.2	26.2	11.8
Charged DOP	.375	-	-	.0223	-	.391	1.99	4.60	10.44
Neutral DOP	32.3	55.2*	-	63.3	-	56.6	36.1	27.3	12.0

3M GO 120							
Size	0.02	0.03	0.05	0.10	0.15	0.20	0.30
Charged NaCl	.00727	.00380	.0233	.00394	.0220	.117	.232
Neutral aCl	8.04	11.8	13.1	8.94	4.93	4.56	1.55
Charged DOP	.138	.0197	.00762	.00420	.00794	.0308	.166
Neutral DOP	9.03	16.1	23.3	19.1	12.8	9.43	5.9

3M GO 130							
Size	0.02	0.03	0.05	0.10	0.15	0.20	0.30
Charged NaCl	.00401	.00151	.00097	.000443	.00103	.00512	.0166
Neutral NaCl	1.40*	3.82	3.70	1.58	.58	.40	.087
Charged DOP	2.13	.104	.037	.0156	.0535	.165	.620
Neutral DOP	3.16	5.62	9.14	4.45	1.78	.58	[-1.0]

* interpolated value

4.6 INTRINSIC PENETRATION OF NEUTRAL PARTICLES THROUGH STANDARD FILTER MEDIA

Returning to the data of Tables VII and VIII, a calculation of intrinsic penetration of neutral particles was made, similar to that for the electrets, and these results are presented in Table XI. Here the difference resulting from introduction of the neutralizer is very much smaller. One can conclude that, over this size range, penetration of uncharged particles is several times as great as for charged. The effect, though discernible, is vastly smaller than for electrets.

TABLE XI

Penetration (%) of Two Filters by Singly Charged Particles (Experimental) and Neutral Particles (Calculated)

HV4A Filter Paper							
Diameter (μm)	.02	.03	.05	.10	.15	.20	.30
Charged NaCl	.000050	.000064	.00204	.0215	.0238	.023	.0082
Neutral NaCl	.000275	.00146	.0098	.0375	.0488	.049	.0062
PALL 10182G Filter Paper							
Charged NaCl	.00026	.00015	.00117	.0123	-	.023	.0048
Neutral NaCl	.00036	.00167	.0097	.0395	-	.0415	.0160

5.0 CONCLUSIONS AND RECOMMENDATIONS

1. Instrumental phenomena observed during operation of the FTS 400 were examined. They are associated in part with the electrical charge borne by the test aerosol, and affect results primarily in the smallest size range. A complete explanation for these irregular results has not been found, nor for the apparent minimum in penetration near 0.02 μm so persistently observed. Some part of the apparently greater penetration of

charged than of uncharged 0.01 μm NaCl aerosol (Figures 1 and 2) is attributable to upstream sampling losses of charged particles. It should be noted that systematic measurements in this size range have not been reported previously. Also, these observations are entirely dependent on a single aerosol generating instrument, the classifier, operating at the lower end of its size range. Results should be confirmed with another generator capable of producing reasonably homogeneous aerosol in the region below 0.01 μm. Several have been described. One is a device of Liu and Kim (6) based on condensation - coagulation; and generators have been described based on vaporization of the source material in an induction furnace and subsequent condensation (7,8).

2. Small DOP and NaCl particles behave quite differently in respect to line losses. The difference could be due to their shapes, spherical droplets and irregularly shaped crystals, but this has not been proven.

3. The role of charge in the capture of particles by conventional (uncharged) filters and by electret filters was briefly examined. The effect is much more significant with electrets, by several orders of magnitude. Pich et al (9) have discussed the theory of electret filter performance in a recent paper. The experimental confirmation of their derivations has not yet been published, and may cast light on this work when it appears.

4. In most polydisperse aerosols produced by practical means only a small fraction of the material is in the size range in which these anomalous results are observed. In many applications the major interest is in the total mass of material traversing the filter, a quantity that varies with the third power of the diameter. In such cases effects at the lower end of the size range are of limited significance. Again, in practical applications the actual charge distribution is neither the Boltzmann equilibrium nor the uniform +1 charge of the classifier output. On balance, however, especially at the smaller sizes (≤0.05 μm), the introduction of a neutralizer between classifier and test chamber is recommended, as the resulting charge distribution is probably more realistic.

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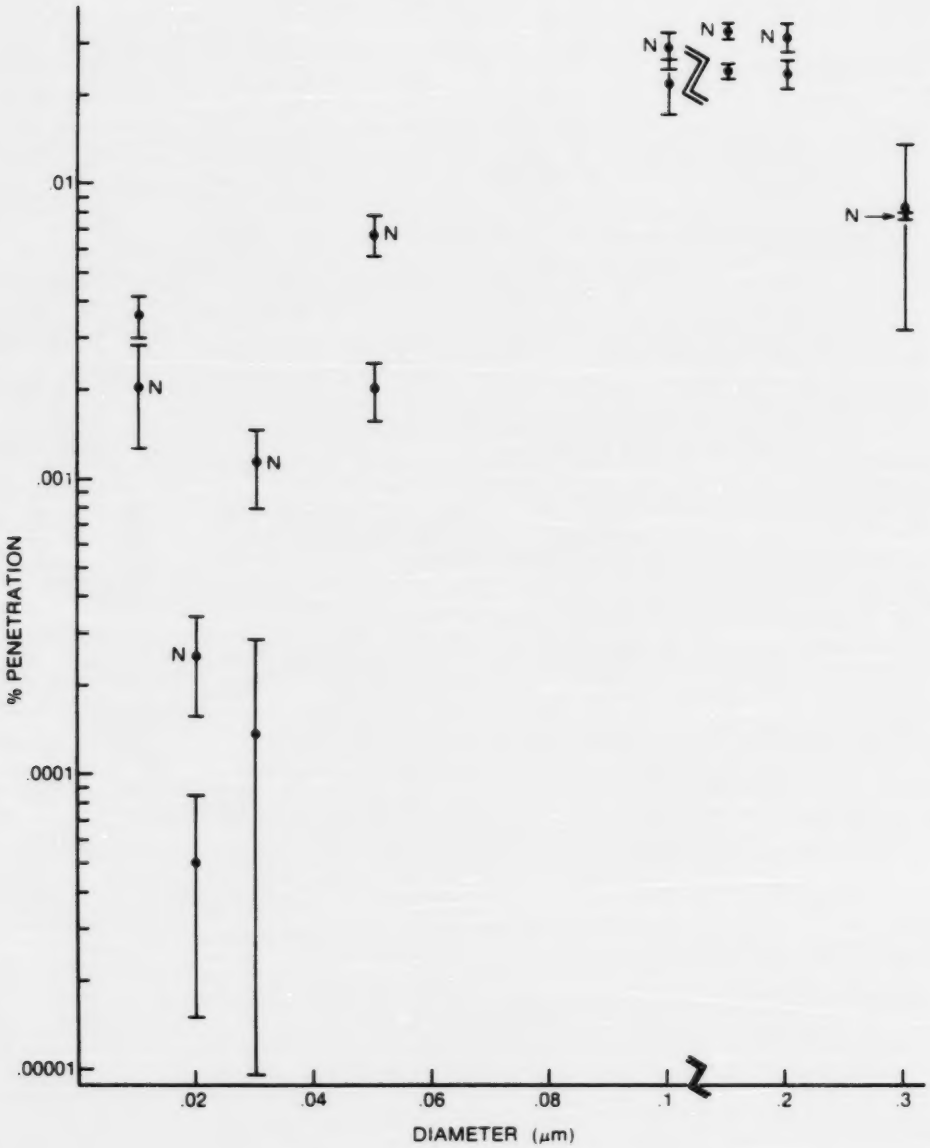

Figure 1: Penetration of HV4A paper by NaCl, in presence and absence of neutralizer.

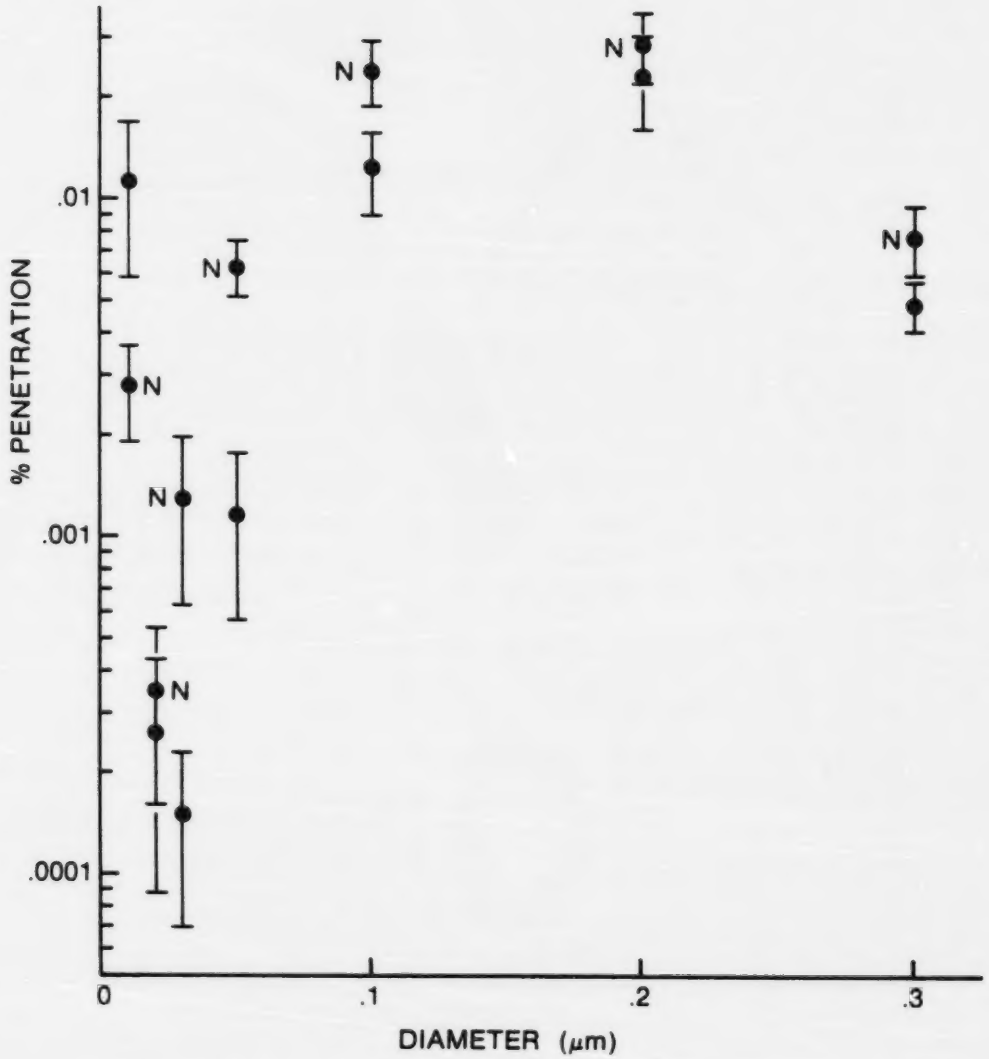

Figure 2: Penetration of Pall 10182G paper by NaCl, in presence and absence of neutralizer.

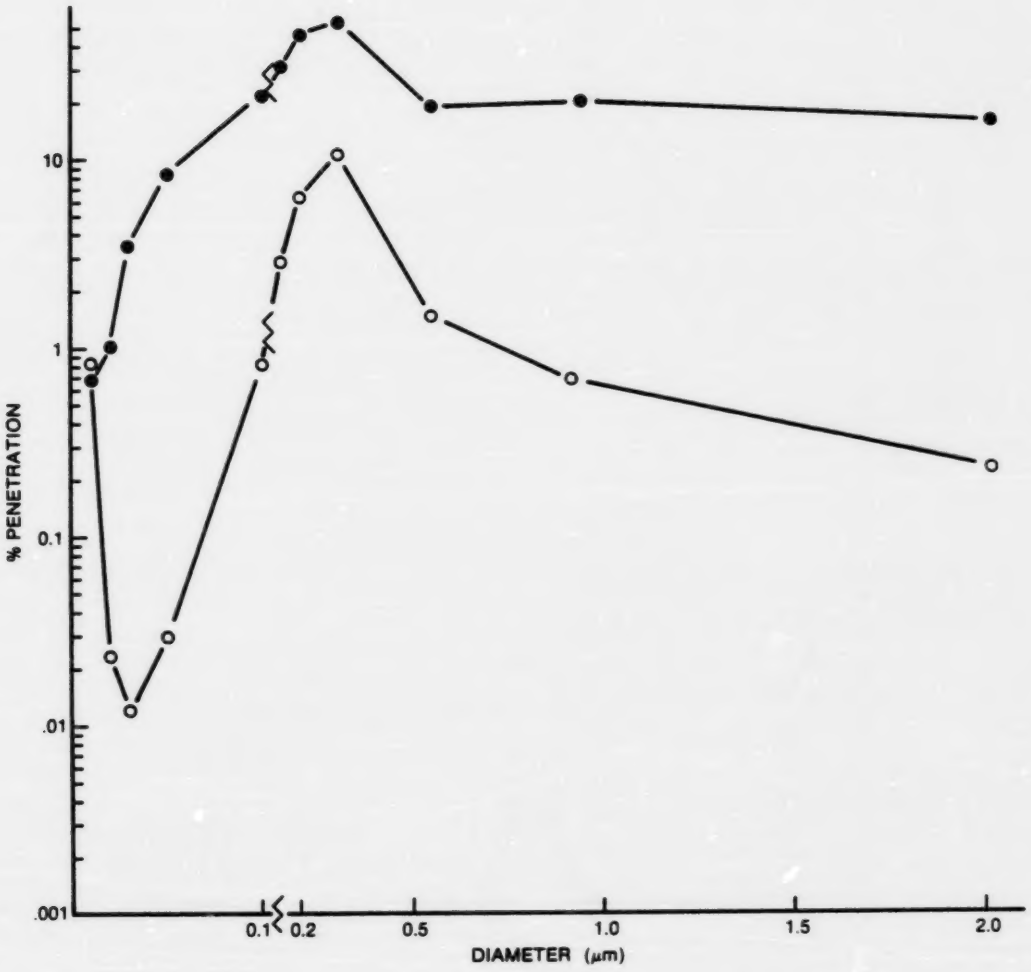

Figure 3: Penetration of 3M GO 110 electret by NaCl, before and after removal of electret charge.

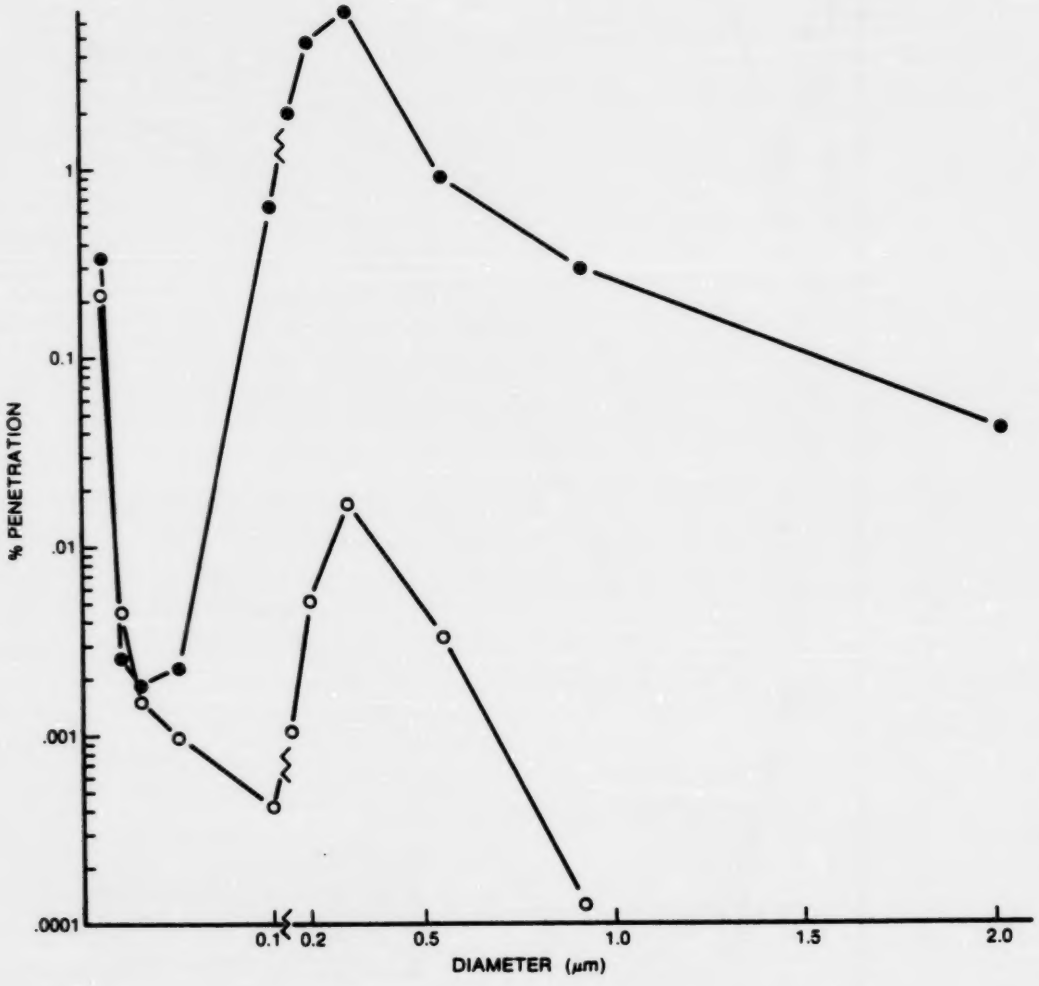

Figure 4: Penetration of 3M GO 130 electret by NaCl, before and after removal of electret charge.

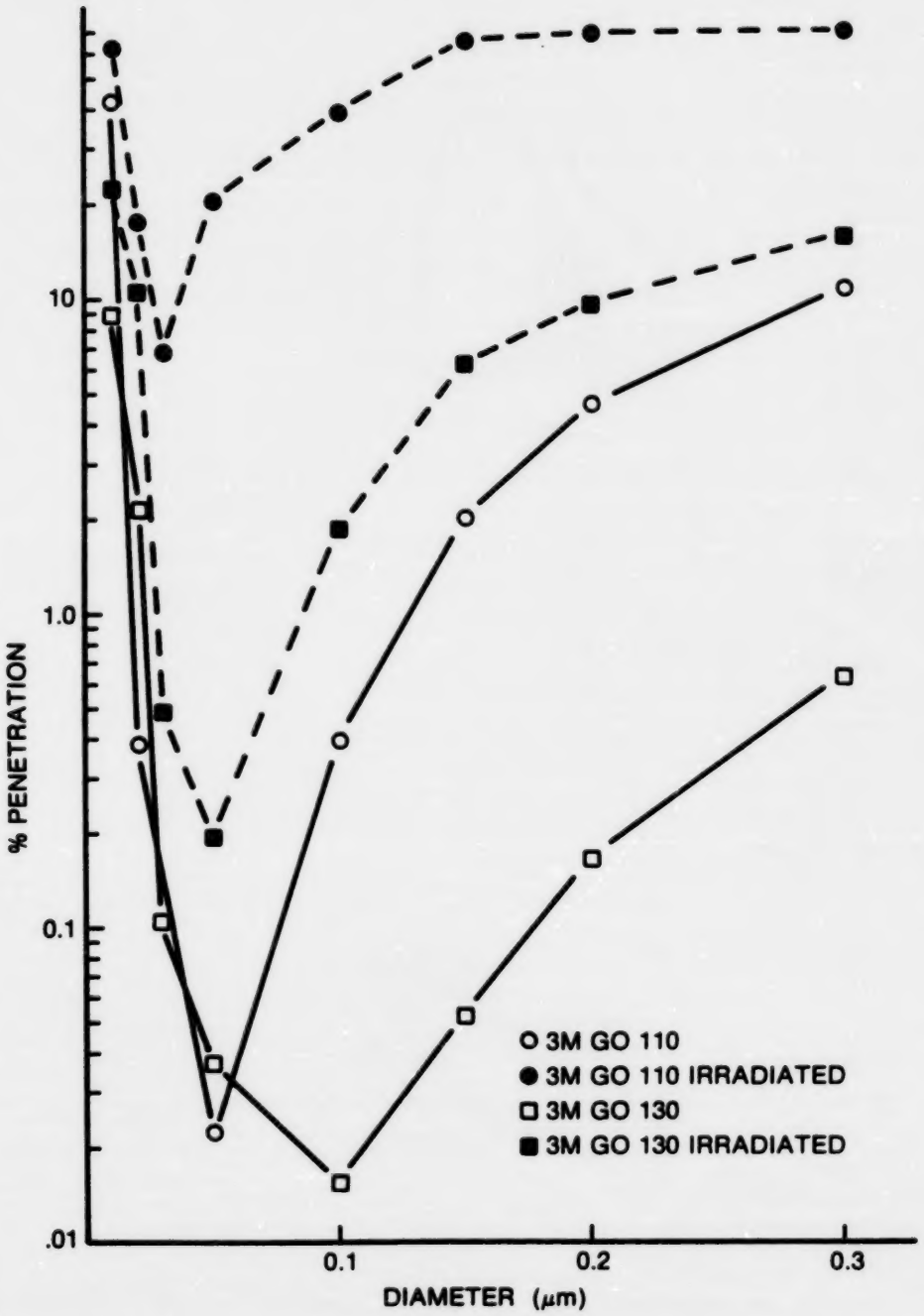

Figure 5: Penetration of 3M GO 110 and 130 electrets by DOP, before and after removal of electret charge.

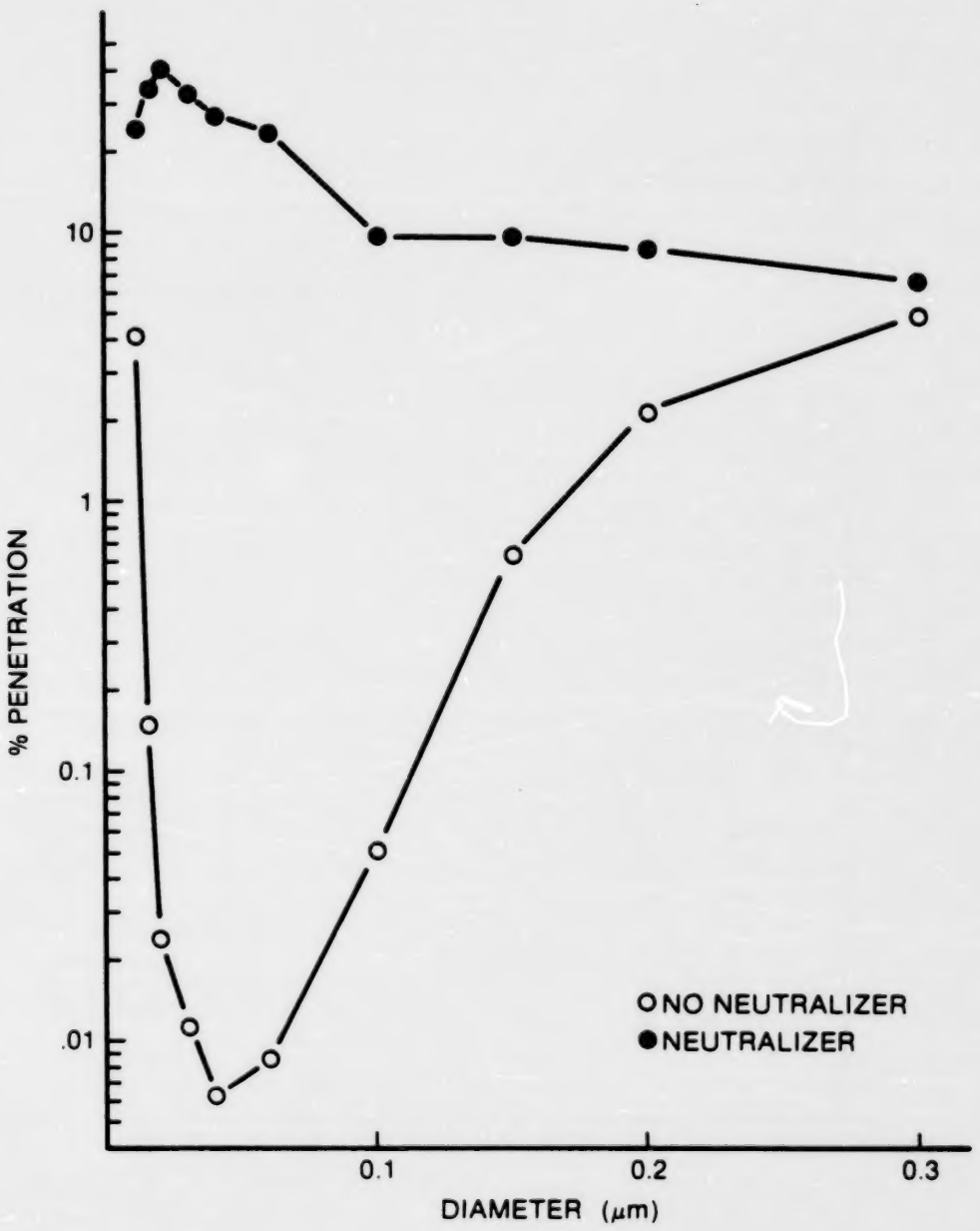

Figure 6: Penetration of 3M GO 110 by NaCl, in presence and absence of neutralizer.

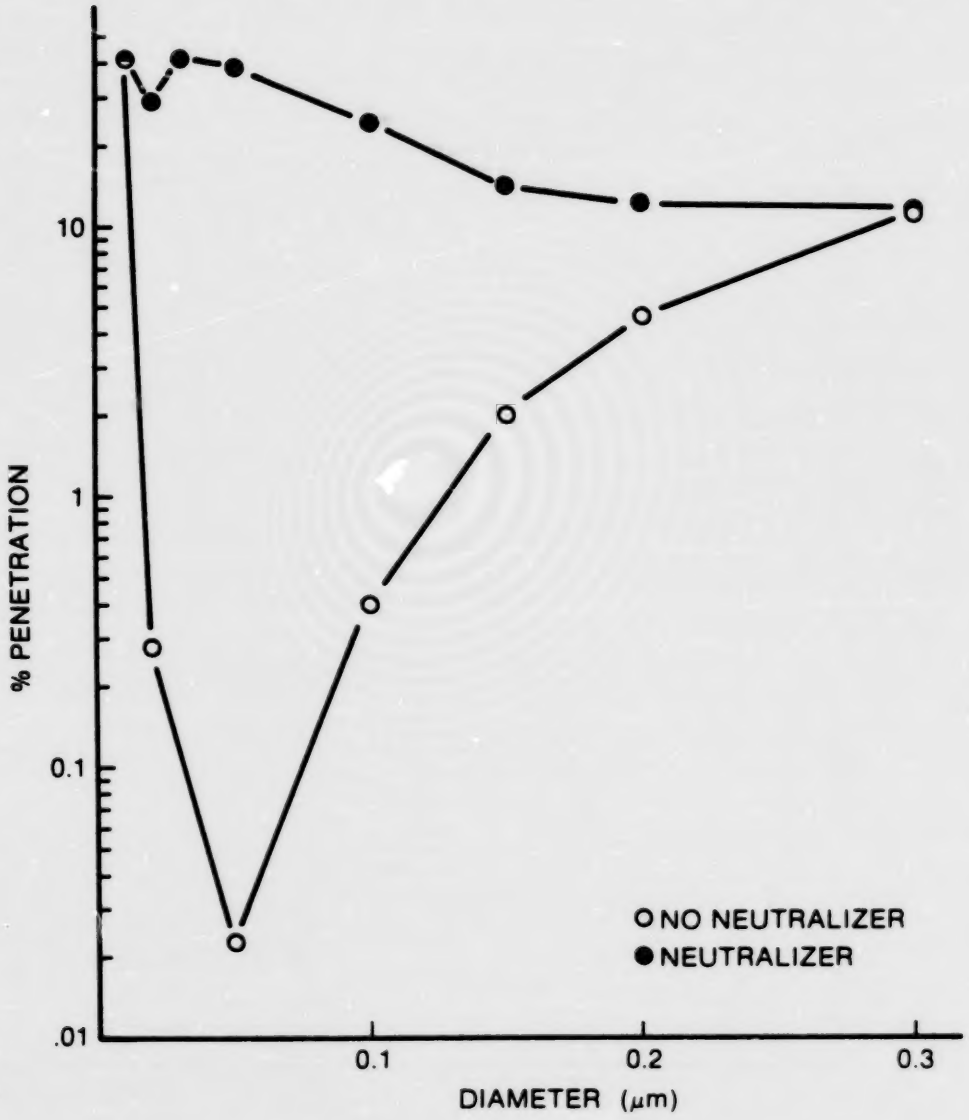

Figure 7: Penetration of 3M GO 110 electret by DOP, in presence and absence of neutralizer.

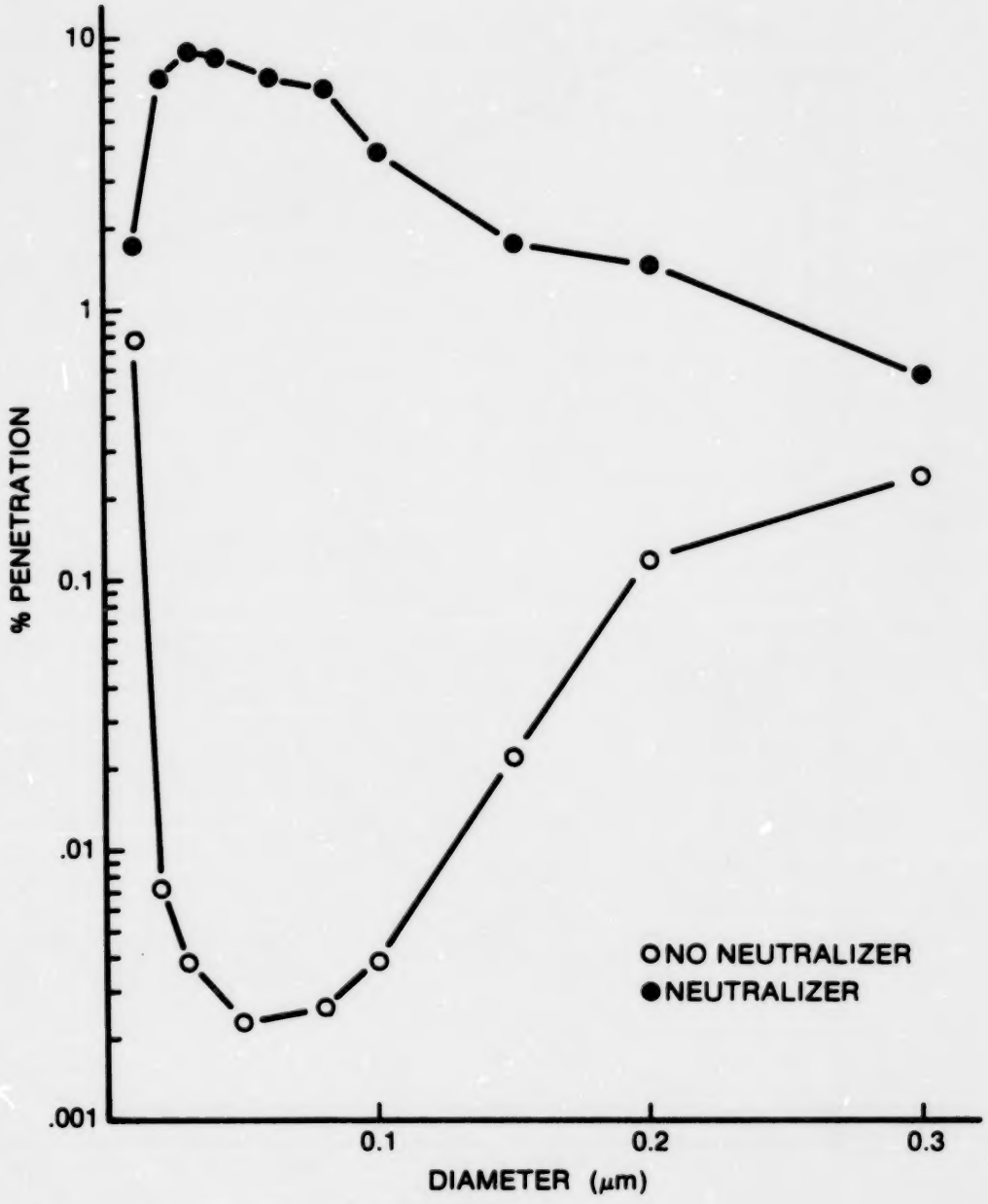

Figure 8: Penetration of 3M GO 120 electret by NaCl, in presence and absence of neutralizer.

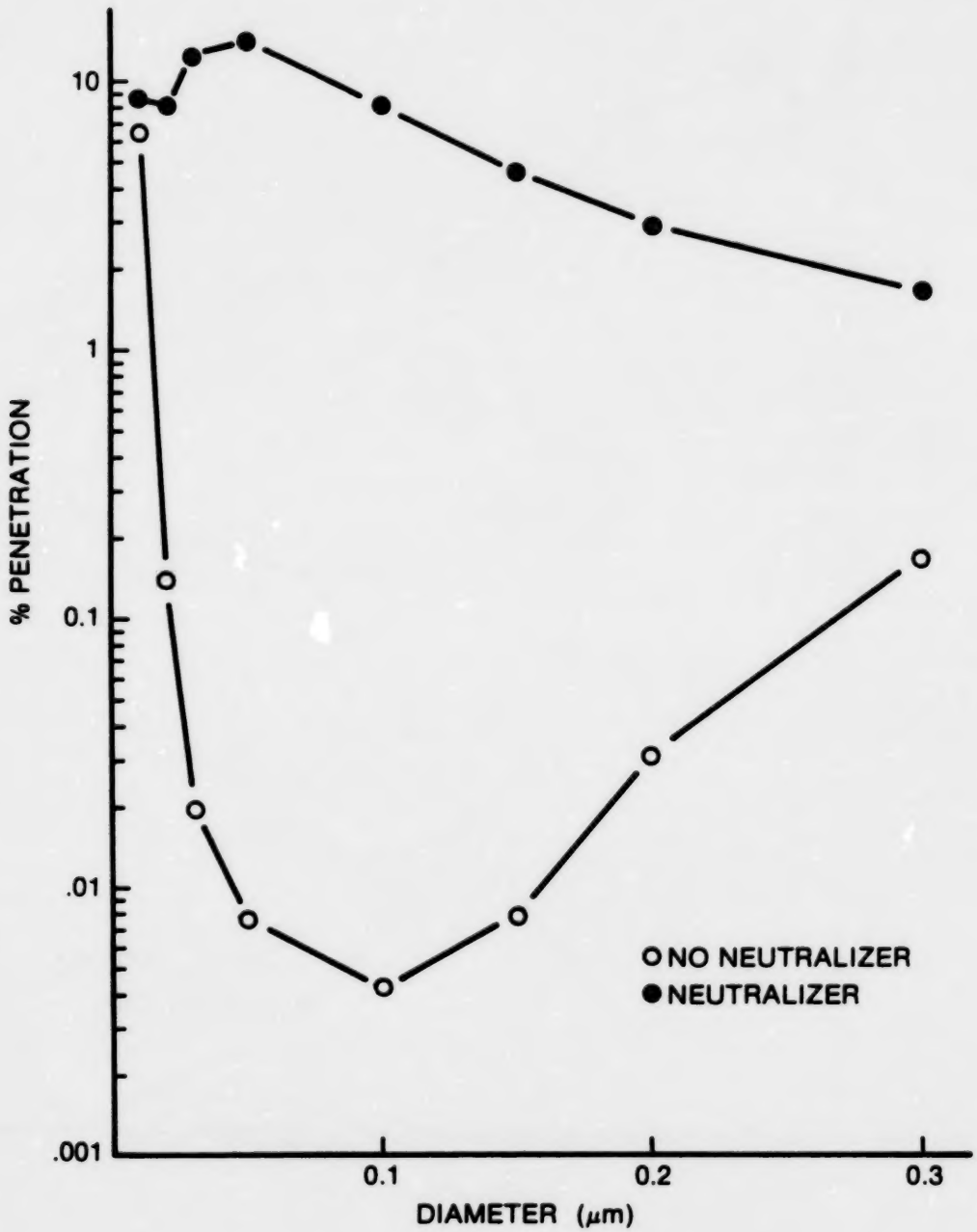

Figure 9: Penetration of 3M GO 120 electret by DOP, in presence and absence of neutralizer.

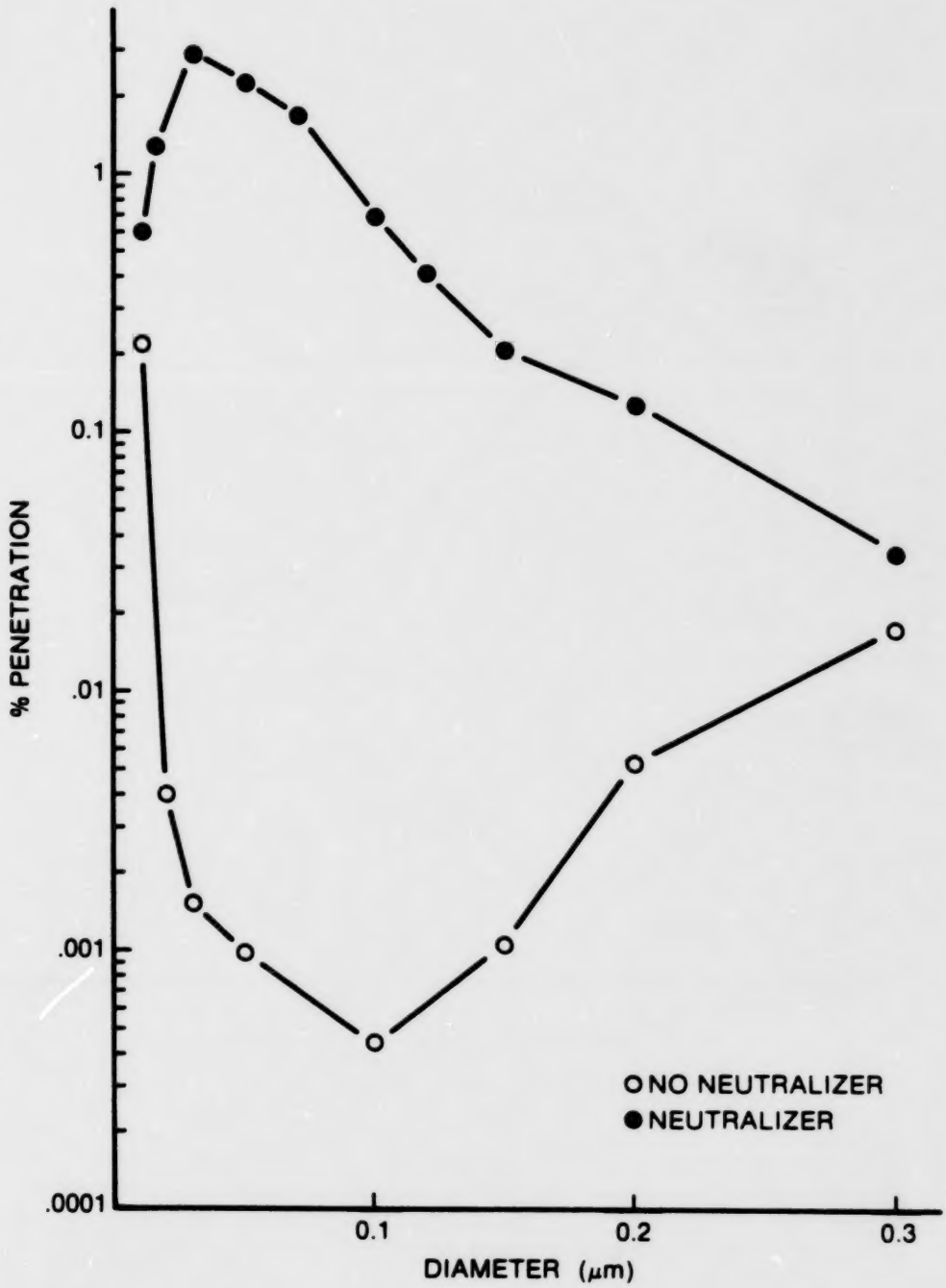

Figure 10: Penetration of 3M GO 130 electret by NaCl, in presence and absence of neutralizer.

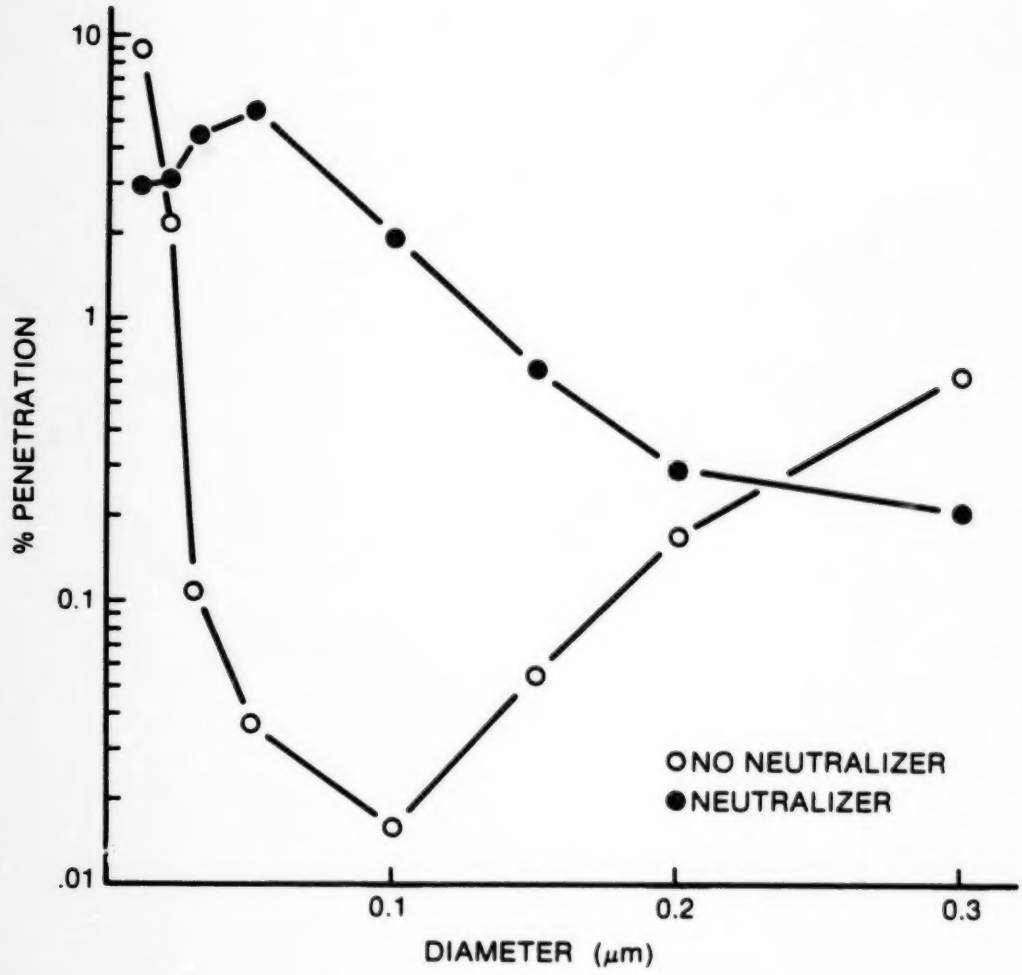

Figure 11: Penetration of 3M GO 130 electret by DOP, in presence and absence of neutralizer.

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The filter test system FTS 400 was used to examine a variety of filter papers, using NaCl and DOP as aerosol challenges. In nearly every case a minimum in penetration was observed at particle size in the vicinity of 0.02 µm. In the same region NaCl particles (but not DOP droplets) exhibited substantial in-line losses which could affect measured penetration results. Introduction of a radioactive neutralizer which removes most of the particle charge greatly reduced line losses.

The effect of introducing the neutralizer on penetration was studied, using several types of filter paper. Conventional filter papers showed a slight increase in penetration over the size range up to 0.3 µm. With electrets, which depend on electrical attraction for their effectiveness, introduction of a neutralizer increased penetration in the same range by several orders of magnitude.

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